Transition between parametric and Raman oscillation in high-Q silica toroidal microcavities

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Abstract: A controlled and reversible transition between parametric and Raman oscillation in a high-Q silica toroidal microcavity is demonstrated. By changing cavity loading and frequency detuning, parametric or Raman oscillation can be accessed without any modification of cavity geometry.

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Kerr-nonlinearity mediated optical parametric oscillation has been demonstrated recently in a tapered optical fiber coupled high-Q silica toroidal microcavity [1]. The transition from the Raman regime to the parametric regime was enabled in part by geometrical control of the toroid shape (i.e., aspect ratio control) to thereby manipulate the parametric bandwidth [2] through reduction of the modal cross-sectional area. In particular, for aspect ratios $D/d > 15$ (where D: major diameter, d: minor diameter, and where $D/d = 1$ is the extreme case of a sphere) a transition to parametric oscillation was frequently observed. Cavity loading is another control parameter that can be used to manipulate this transition and which has not yet been studied experimentally. In this paper, we demonstrate control of oscillation regime (Raman-only, parametric-only and Raman-parametric oscillation) under fixed input pump power by varying the loading conditions for a toroidal microcavity of fixed, but sufficiently high, aspect ratio to enable parametric oscillation.

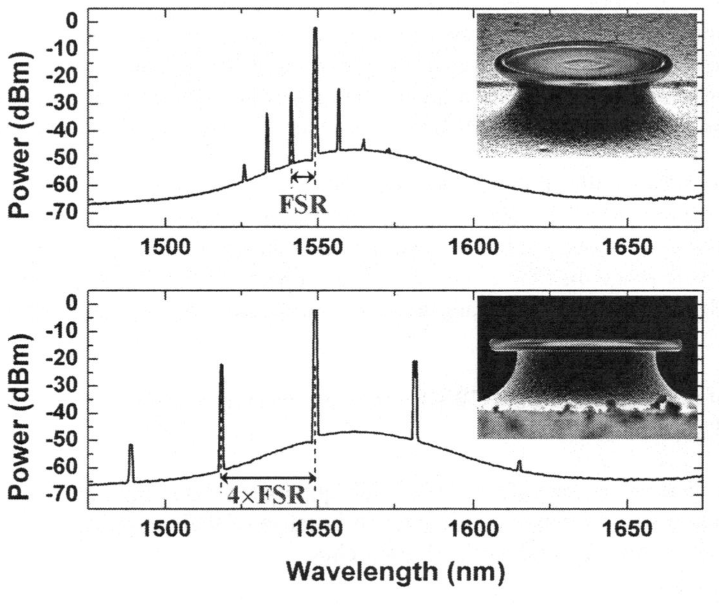

Fig.1. Two parametric oscillation spectra measured from the same high-Q silica toroidal microcavity with minor (d)/major (D) diameter of 3.8/67 μm ($D/d = 17.63 > 15$). The two spectra correspond to a different (horizontal/vertical) tapered fiber position with respect to the toroidal microcavity. Inset: SEM micrograph of a toroidal microcavity used for these spectra.

Fig. 1 shows two typical optical spectra of Kerr-nonlinearity induced parametric oscillation in a high-Q silica toroidal microcavity with minor/major diameter of 3.8/67 μm. These two spectra are observed in the same toroidal microcavity. Signal and idler oscillation wavelengths (including the pump mode) correspond to the fundamental TE modes (which can be shown to have a smaller effective mode area than the TM modes: $A_{eff}^{TE} < A_{eff}^{TM}$ and hence have a larger parametric gain bandwidth) of the toroidal microcavity and the corresponding free spectral range (FSR) is ~7.8 nm. In toroids studied, the minimum intrinsic Q-factor (Q_0 of the pump mode) was 0.7×10^8. Tapered optical fiber of ~2 μm-diameter was used to couple pump and emission to/from the toroidal microcavity for characterization. The inset in Fig. 1. shows a scanning electron microscope (SEM) image of the actual toroidal microcavity.

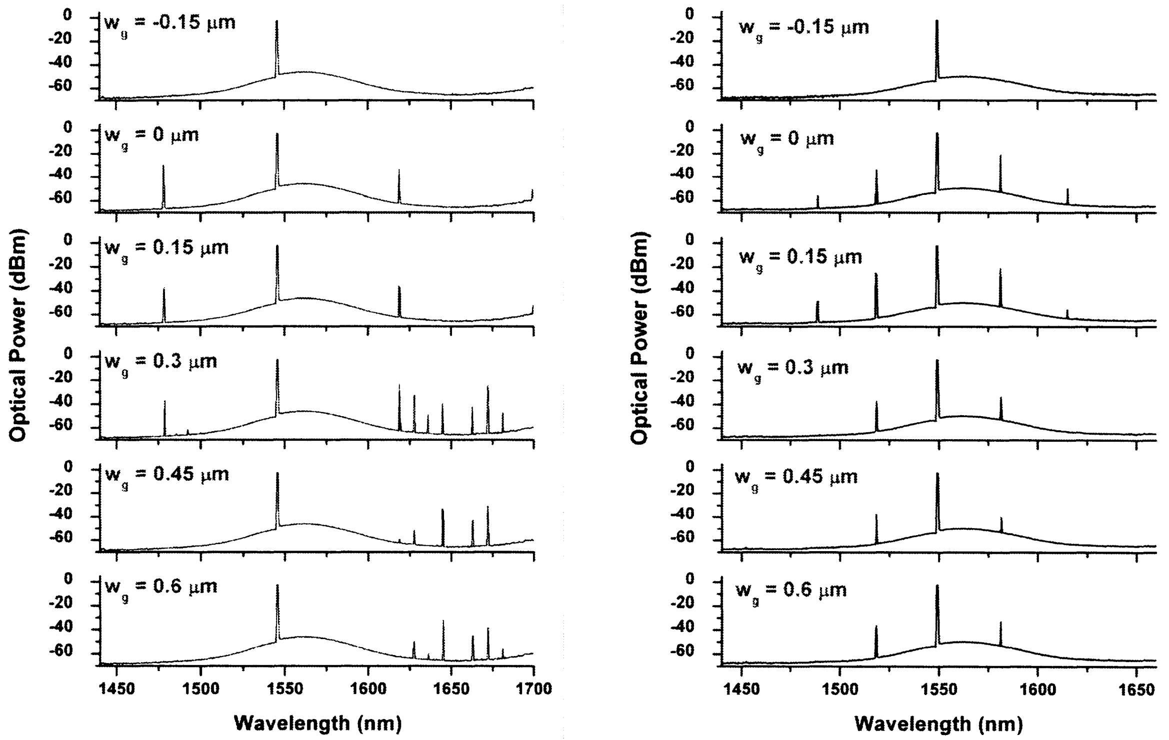

Fig. 2. (a) Transition between Raman oscillation and parametric oscillation in a toroidal microcavity with larger frequency mismatch $\Delta\omega$. Note that there is a range of cavity loading conditions in which both parametric and Raman oscillations coexist. (b) Toroidal microcavity with smaller frequency mismatch $\Delta\omega$ showing parametric-only regimes over a range of loading conditions. Cavity loading is controlled by adjustment of the taper-cavity gap distance shown in each plot. Gap is given relative to the critical-coupling gap distance and loading increases in the vertical direction.

Fig. 2.shows spectra taken from the same toroidal microcavity having different frequency mismatch $\Delta\omega$ (by changing the pump wavelength). Cavity loading increases vertically in each column of spectra. In each graph, input pump power was fixed below ~1 mW and only the cavity loading has been changed by varying the tapered fiber position. In (a), the transition from Raman oscillation to Raman-parametric oscillation and eventually to parametric-only oscillation (cavity loading changed gradually from under-coupled to over-coupled regime) is clearly demonstrated as a function of cavity loading. This kind of transition from Raman to parametric oscillation is a clear signature of intermediate to large phase-mismatch frequency [1]. In contrast, only the parametric oscillation regime can be observed under fixed input pump power condition over the range of loading in data in the right column. Here, the toroid has a smaller frequency mismatch (estimated $\Delta\omega/2\pi <$ ~10 Mhz where $\Delta\omega = 2\omega_P-\omega_S-\omega_I$). Even though it is not shown explicitly in Fig. 2., the Raman-only regime also can be observed from the same toroidal microcavity.

In conclusion, a cavity-loading induced transition between Raman and parametric oscillation in high-Q silica toroidal microcavity has been demonstrated. Frequency detuning $\Delta\omega$ and the cavity loading play important roles in the operation of microcavity nonlinear oscillators. It is possible to observe various oscillation regimes ranging from parametric to Raman or both in the same toroidal microcavity by variation of cavity loading conditions. Additionally, these devices can also be designed to render them relatively insensitive to this loading induced transition, enabling operation in either parametric or Raman regimes.

References

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